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Hydrocarbons

KNOWN DISTRIBUTION AND TYPES OF HYDROCARBONS

Evidence for the presence of hydrocarbons in Cuba is extremely widespread. Tar deposits, bituminous limestones, gas and oil seeps, and small producing fields are common throughout the island. Asphalt deposits were commercially mined at the turn of the century. The estimated daily production of the island was 34,000 BOPD for 1999 (Torres, 1999). However, to this date, despite the efforts by major western oil companies prior to the late 1950s (such as Chevron, Esso, Gulf, Shell, and Texaco), and those of many independents, plus the Eastern Block–Cuban cooperation since then, no major hydrocarbon accumulation has been found.

The petroleum indications show a definite distribution pattern. The past and presently producing fields can be considered extensions of the seeps and therefore will be described under the same headings.

For a general distribution of oil fields and petroleum indications, see Cuba, 1988. Known oil-field statistics are tabulated in Table 1.

Central Cuba

The occurrence of seeps will be described according to the geologic province or belts in which they are located. See Figure 194.

Yaguajay* and Coastal Area

With the exception of a few tar indications (tar balls out of fractures in outcrops), no seeps are known from the Yaguajay* belt and coastal area. However, in Gulf Blanquizal-1, Shell Cayo Coco-2, Shell Manuy-1, and Texaco Mayajigua-1, all drilled in the coastal region or in the Yaguajay* belt, small traces of hydrocarbons were reported. These commonly consisted of tar in samples and small amounts of gas in drill-stem tests (DSTs). Dry ammonia gas and minor amounts of methane were recovered in Shell Cayo Coco-2 DSTs. Nothing is known about the deep wells drilled by ICRM.

Sagua La Chica* and Jatibonico* Belts

Only a few tar indications in fractures are present in the Jatibonico* belt.

Las Villas* Belt

Surface Indications

Very few surface seeps are found in the outcrops of Las Villas* belt lithologies. However, these lithologies are reported to be productive in northern Cuba. Many fresh samples of these rocks collected from below the surface (core drill, fresh road cuts) show common oil-filled fractures and vugs, suggesting that the exposed limestones had contained oil at one time and lost it through weathering.

Subsurface Indications

Two wells drilled in the Las Villas* belt had abundant hydrocarbon indications; Gulf Hicacos-1 and Gulf Guayabo-1. Hicacos-1 will be discussed under northern Cuba.

Texaco Guayabo-1. It had common tar, heavy oil, and occasional gas to total depth at 10,010 ft (3052 m). The shows became more common below a thrust fault at 2910 ft (887 m), with Jaguita* overriding the Calabazar* Formation. The Calabazar* and Ramblazo* formations had no porosity or oil shows. The Capitolio* Formation had rare oil shows, and these were commonly associated with some dolomitization. The Upper Jurassic Caguaguas*, Jaguita*, and, possibly, Hoyo Colorado* formations had common dolomitization and abundant shows of 1–5° API tar. Some cores bled gas for several days after having been cut. A fractured limestone interval at 7628–7632 ft (2326–2327 m)

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Name	Year	Lithology	Age	Depth Ft	Depth Mt	Belt	Trap	Grav API	% S	Av.Prod BOPD	Cu.Prod MBO	Ult.Rec MMBO	Discovery Method
Bacuranao	1914	Serp.	Pre-UK	2625	800	Dom.-Cabai.	Fault-Lith.	24	1.04	73	450	<1	Oil seeps
Boca de Jaruco	1969	Lmst.	UJ-LK	4925	1500	Las Villas	Thrust-Lith.	17	4.52	2591	8163	20	Seismic
Boca de Jaruco II	1990	Lmst.	UJ-LK	5525	1700	Las Villas	Thrust-Lith.			?	?	?	Dev. well
Camarioca	1971	Serp.- lmst	Pre-UK	2625	800	Dom.-Cabai.	Fault-Lith.	32	0.18	153	363	?	Seismic
Cantel	1978	Chert - Lmst	Apt-Alb	3940	1200	Las Villas	Thrust-Lith.	15	1.47	1.54	3849	?	Gravimetry
Cantel	1978	Serp.	Pre-UK	1650	500	Dom.-Cabai.	Fault-Lith.	11	1.53	?	?	?	Gravimetry
Catalina	1956	Tuff-Lmst.	UK	5900	1800	Cabaiguan	Fault-Uncon.	31	1.78	Abd.	15	<1	Seismic
Chapelin	1971	Lmst.	UJ-LK	5900	1800	Cifuentes	Thrust-Lith.			Abd	?	?	Seismic
Cristales	1954	Tuff-Cgl.	UK	3280	1000	Cabaiguan	Fault-Uncon.	22	0.97	326	830	8	Seismic
Guanabo	1968	Serp.	Pre-UK	2950	900	Dom.-Cabai.	Fault-Lith.	11	3.8	27	127	<1	Surf. geol-seismic
Guásimas	1974	Lmst.	Apt-Alb	4925	1500	Las Villas	Thrust-Lith.	10	4.66	243	609	?	Subsf. correl.
Jarahueca	1943	Serp.- Lmst.	Pre-UK	2625	800	Dom.-Cifuen.	Fault-Lith.	38	0.24	16	1620	1.7	Oil seeps
Jatibonico	1954	Tuff	UK	1650	500	Cabaiguan	Fault-Uncon.	14	2.02	79	1819	5	Gravimetry
Litoral Piedra	1990	Lmst.	UJ-LK	5525	1700	Las Villas	Thrust-Lith.	27		41	30	<1	Seismic
Marbella	1975	Lmst.	UJ-LK	4265	1300	Las Villas	Thrust-Lith.			46	46	<1	Develop. well
Marbella Mar	1989	Lmst.	UJ-LK	7545	2300	Cifuentes	Thrust-Lith.			?	?	?	Seismic
Martin-Mesa	1989	Lmst.	UK	4265	1300	Las Villas	Thrust-Lith.	19	1.49	95	36	?	Surf. geol.
Motembo	1881	Serp.	Pre-UK	650	200	Dom.-Cabai.	Fault-Lith.	61	0.004	5	1750	?	Gas seeps
Peñas Altas	1956	Serp.	Pre-UK	2625	800	Dom.-Cabai.	Fault-Lith.	10	2.94	3	4	?	Oil seeps
Pina	1989	Tuff-Cgl.	UK	2950	900	Cabaiguan	Fault-Uncon.	28	1.54	500	194	<1	Gravimetry
Sta.Maria	1956	Serp.	Pre-UK	5280	1600	Dom.-Cabai.	Fault-Lith.	22	2.54	14	61	<1	Develop. well
Varadero	1971	Lmst.	UJ-LK	4925	1500	Las Villas	Thrust-Lith.	12	7.29	6534	11,239	50	Seismic
Varadero Sur	1974	Lmst.	Apt-Alb	4925	1500	Las Villas	Thrust-Lith.	20	3.08	156	375	?	Develop. well
Vía Blanca	1968	Lmst.	Apt-Alb	4100	1250	Las Villas	Thrust-Lith.	20	2.78	?	?	?	Surf geol.
Yumurí	1971	Lmst.	UJ-LK	4925	1500	Las Villas	Thrust-Lith.	16	5.62	52	50	?	Grav.seis.

Table 1. Oil fields. Modified from Echevarria-Rodriguez et al. (1991) and G. Pardo, 1992, The Geology of Cuba Petroconsultants report.

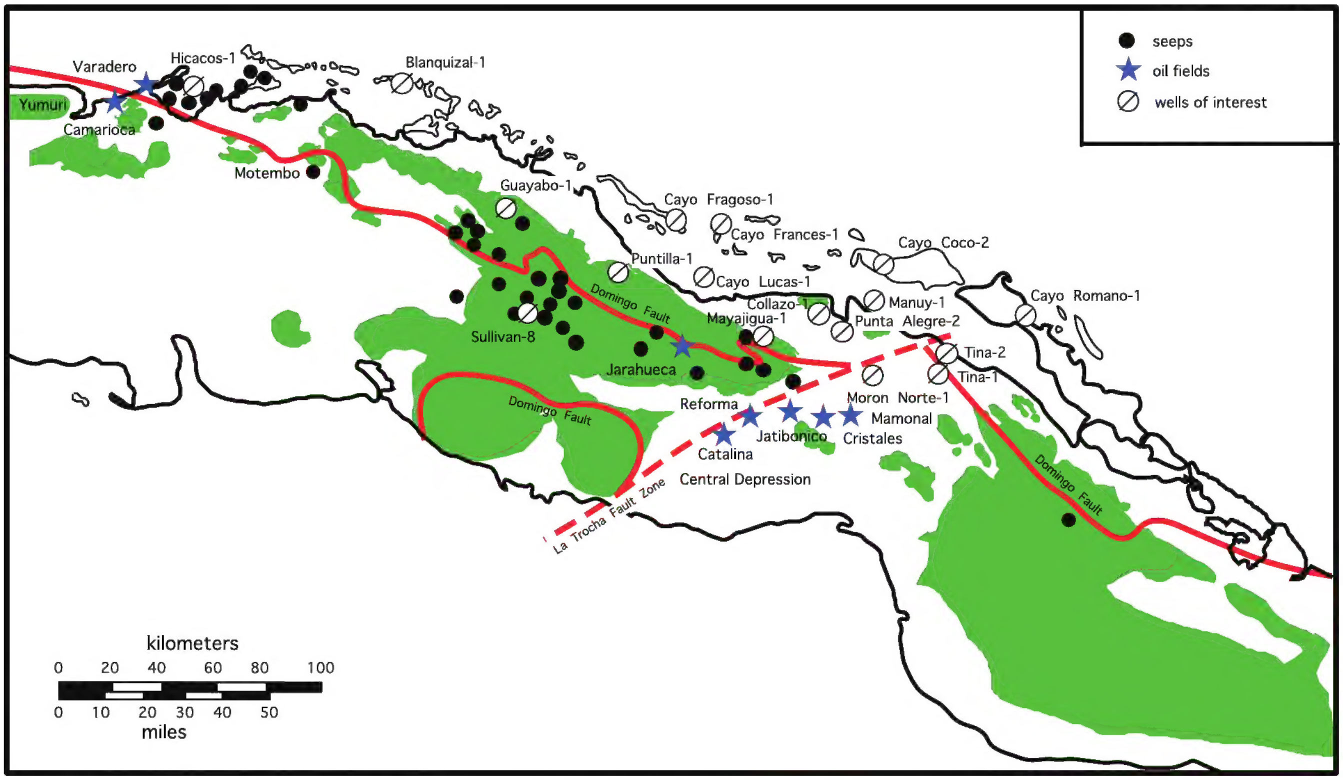

FIGURE 194. Central Cuba: petroleum seeps, oil fields, and significant wells.

oozed 5° API tar every time drilling was stopped. On test, this interval produced 4 bbl of tar and a small amount of gas.

Placetas and Cifuentes* Belt, Domingo* Sequence*

Most surface petroleum indications occur in the general area between the southern boundary of the Domingo* sequence and the southern boundary of the Las Villas* belt. This relationship extends from Habana to Oriente, although the complete succession of belts is present at the surface only in Las Villas and northwestern Camaguey (Wassall, 1956). In the subsurface, several accumulations occur in the upper part of the Cifuentes* and Placetas belts and below or within the base of the Domingo* sequence.

Surface Indications

Within these belts, the seeps can be differentiated into two groups according to their character:

1) The first group consists of a zone of asphalt occurrences, more or less parallel and close to the Domingo* fault separating the Domingo* and Cabaiguan* sequences from (a) the Las Villas* belt to the southeast and (b) the Cifuentes* belt to the northwest. The asphalt invariably fills fractures in the Placetas*, Cifuentes*, and Domingo* belt rocks or even occurs as dikes in basic igneous rock. These dikes can be quite large; the Jatibonico asphalt dike is several meters thick and more than 1 km (0.6 mi) long.
   Core drilling north of the town of Placetas (north of the above-mentioned fault zone) found abundant oil shows. In the neighborhood of the fault plane, the oil had gravities ranging from 15 to 35° API. In some cases, these shows came from boulders in Vega* or Rosas* Formation conglomerates, which displayed pressure release when broken. It therefore appears as if the original Domingo* thrust fault (presently a high-angle fault, or cut by a high-angle fault, with a left-lateral component) was at some time responsible for the migration and accumulation of hydrocarbons. The open, asphalt-filled fractures in its vicinity, as well as the vertical asphalt dike near Perea, are evidence that this process occurred under geostatic pressure conditions at great depth.
2) The second group of seeps is characterized by heavy to medium-gravity oil and gas; these occur in abundance over most of the Domingo* sequence, south of the Placetas* and Cifuentes*

belts. They are particularly well developed in a large area of serpentine outcrops (commonly containing abundant metamorphic exotics) near the town of Santa Clara. Some of the seeps are quite active and have been the basis for the development of most of the Cuban oil fields. A gas seep near Potrerillo produced an estimated 1440 ft^3/day (40.8 m^3/day). In addition, many water wells and core holes drilled in the area have had petroleum indications. One core hole (Sullivan Core Hole-8) was drilled by Gulf to 2343 ft (714 m) in 1955 in the center of the above-mentioned serpentine area, which was interpreted at the time to represent the crest of a large, anticlinally folded thrust sheet of ultrabasics. The hole was drilled for several reasons, but one of them was to find out if the very active seeps in the vicinity were an indication of a larger accumulation and/or a proximity to a different lithology at depth. A strong show of 39° API oil was encountered at 278 ft (85 m), and several barrels were produced. Unfortunately, no further shows were encountered to total depth. Brown & Root Laboratories, Inc. analyzed a sample of that oil sent to Tenneco. Their report, dated October 17, 1985, showed that the sample exhibited no obvious indication of biodegradation and the saturate fraction of the sample was very paraffinic. The percentage of naphtenes was not available but the report related that a visual examination of the gas chromatogram indicated the percentage was likely to be very low, suggesting an origin from a terrestrial or mixed terrestrial-marine source. Brown & Root Laboratories reported that normal alkenes were present in the sample out to approximately C_{35+}, which further suggested a terrestrial influence. Because of the terrestrial aspects of the sample, the report concluded that a clastic rather than a carbonate source rock was favored.

This conclusion is supported by an older Gulf Research & Development Co. analysis that reports 3.72% wax for the same oil. As will be seen later, this conclusion presents serious interpretation problems because the obvious source rocks are predominantly marine carbonates.

Note that whereas the seeps in group 1 exhibit heavy and relatively immobile oils, those in group 2 produce much lighter petroleum and are quite active as though they were generated at depth by a source that is active today. In other words, the Domingo* sequence rocks appear to behave as a leaky cap over some accumulation (or hydrodynamic drive) at depth.

Oil Fields

Jarahueca field.— This field, discovered in 1943, is located on the complexly faulted flank of the Jarahueca window and yielded 37–40° API oil and some gas from basic igneous rocks (mostly from serpentine) and fractured limestone. However, the wells spudded in basic igneous rock commonly produce an oil of light-yellow color, in contrast to those spudded in the carbonates of the Cifuentes* and Placetas* belts, which produce a nearly black oil. No significant difference exists in API gravity. The meaning of this observation is not clear, but it seems to suggest that at this locality, the outcropping carbonate-igneous fault contact separates two types of oil in the subsurface. The fault must therefore act as a seal.

The production behavior of the wells in this field suggests accumulation in fractured, low-permeability reservoirs; some wells have had initial production rates on the order of several hundred barrels of oil per day, dropping in a few days, and stabilizing for long periods of time at rates ranging from 1 to 20 BOPD. In view of the fact that most of the wells drilled prior to the late 1950s were shallow (less than 3500 ft [1100 m]), whether they reached a common reservoir or instead penetrated feeders to seeps is questionable. The field is reported to have produced a maximum of 960 BOPD in 1947. However, later, the production became very irregular, dropping between 160 and 18 BOPD from 1949 to 1964. In 1964, the last reporting date, the production was at 22 BOPD.

Motembo field.— This field was discovered in 1881, but did not commercially produce until 1890. The maximum production was 465 BOPD in 1940 and has declined steadily since then. In 1964, the production was 6 BOPD. The production is entirely from serpentine and consists mostly of naphta (55–65° API). Some gas as well as some heavier yellow and black oil are observed. The field is located near the contact between the Domingo* and Cifuentes* sequences, and the production characteristics are similar to those of Jarahueca. A southern extension of the field is called Vesubio.

Cabaiguan Sequence*

Surface Indications

This belt is impressively devoid of surface petroleum indications. Only a few petroleum occurrences are reported: one near Ranchuelo, in the Paleogene cover of the axis of the Seibabo syncline; and one in Habana Province, invariably in proximity to the Domingo* sequence rocks. This is somewhat of a puzzle

because the oil fields of the Central Depression are underlain by the Cabaiguan* sequence, and the volcanic section, although of general low permeability, is cut by many faults that should allow some seepage such as in the Jatibonico and Catalina fields.

Oil Fields

Five fields exist, Catalina, Cristales, Jatibonico, Mamonal, and Reforma, which are known as the Central Depression fields. They occur in or near the western flank of the structural low believed to be associated with the La Trocha fault zone. As already mentioned, it is a thickening of the Paleocene to lower–middle Eocene flysch overlying the Cabaiguan* sequence. Upper Eocene and younger beds are not affected.

Jatibonico field.— The Jatibonico field is located on the flank of the Central Depression and appears to be associated with seeps coming up the Arroyo Blanco group of faults. The oil seems to have migrated along the faults, as in Jarahueca, and accumulated in the volcanics under the Tertiary cover. The discovery well, General Corporation Echevarria-1, drilled in 1954, found 15° API oil at 1072 ft (327 m) in fractured volcanics of the Cabaiguan* belt under the Paleocene(?)–Eocene unconformity. Echevarria-1 was drilled to 8375 ft (2553 m) and remained in Cabaiguan* sequence volcanics to total depth and never encountered any carbonates or ultrabasics. The gross pay thickness is reported as 230 ft (70 m). EPEP Jatibonico-78, drilled less than 2 km (1.2 mi) to the southwest, penetrated the Cabaiguan* sequence at 1150 ft (350 m) and remained in the volcanics until 13,775 ft (4200 m), where it is reported to have penetrated pre-Jurassic(?) metamorphics to a total depth of 15,553 ft (4437 m). It is not known if these metamorphics are similar to those of the Escambray massif or of the Manicaragua belt. The maximum annualized production rate was 1230 BOPD in 1957. By 1963, the production had declined to 170 BOPD, and secondary recovery projects were initiated in 1964.

Catalina field.— The Catalina field is located 13 km (8 mi) southwest of Jatibonico. The discovery well Drilling Catalina-1, drilled in 1956, found production of 32–35° API below 7102 ft (2165 m) in limy, fractured Catalina Shale. The total depth was 7157 ft (2181 m). Although this shale has been reported to be of Upper Cretaceous age, in this report, it is considered equivalent to the Paleocene Taguasco* and Fomento* formations. The situation appears to be similar to that of Jatibonico, with oil migrating up faults and accumulating at or near the Paleocene unconformity. The gross pay is reported to be 18 ft (5 m), and the maximum annualized production was 26 BOPD in 1957.

Cristales field.— Located some 25 km (15 mi) to the east of Jatibonico, the Cristales field appears to be of a similar in nature. The discovery well Cuban American Cristales-1A, drilled in 1956, found a gas accumulation below ±1800 ft (±550 m) in fractured vugular reef limestones of the Jiquimas* Formation (Cristales Limestone) of Maastrichtian age interbedded with volcanics. The depth of the productive interval averages 2600 ft (800 m). This section underlies the Paleocene unconformity. Oil shows were also found in the underlying volcanic sequence. This field was considered the first commercial gas discovery in Cuba. The initial tests gave 1 MMCFGD, and gas production began in 1971 and reached 2 MMCFGD in 1974. Oil was also being produced at the rate of 370 BOPD in 1964.

No published information exists on Mamonal and Reforma fields, but they are believed to be of the same size as the Catalina field.

It should be noted that oils from the Catalina and Cristales fields (Gurko et al., 1982) show great similarity to Jarahueca oils, including indication of meteoric loss of higher fractions, low asphaltenes, and a paraffinic composition of 28–69% (as in Gulf Sullivan-8, a suggestion of terrestrial influence).

Numerous wells (most of them shallow) were drilled in the same La Trocha graben, farther southwest (in the vicinity of Sancti Spiritus), with no reports of oil indications.

Western Cuba: Pinar Del Rio

The Viñales Group of limestones has long been known as a petroliferous section in the Rosario Mountains and in the Martin Mesa window. The San Diego de los Baños Basin, with its well-developed Tertiary section, has also attracted much attention in the past. Recently, the northwest coast of Pinar del Rio, in the Esperanza belt, has been the subject of an unsuccessful exploration and deep drilling program. See Figure 195.

Northern and Southern Rosario and La Esperanza Belts

Surface Indications

Most of the oil indications in Pinar del Rio are restricted to these belts. They consist mostly of heavy-oil-filled fractures in the Jurassic and Lower Cretaceous carbonates. The Maastrichtian fragmental limestones commonly bleed oil, and asphalt veins

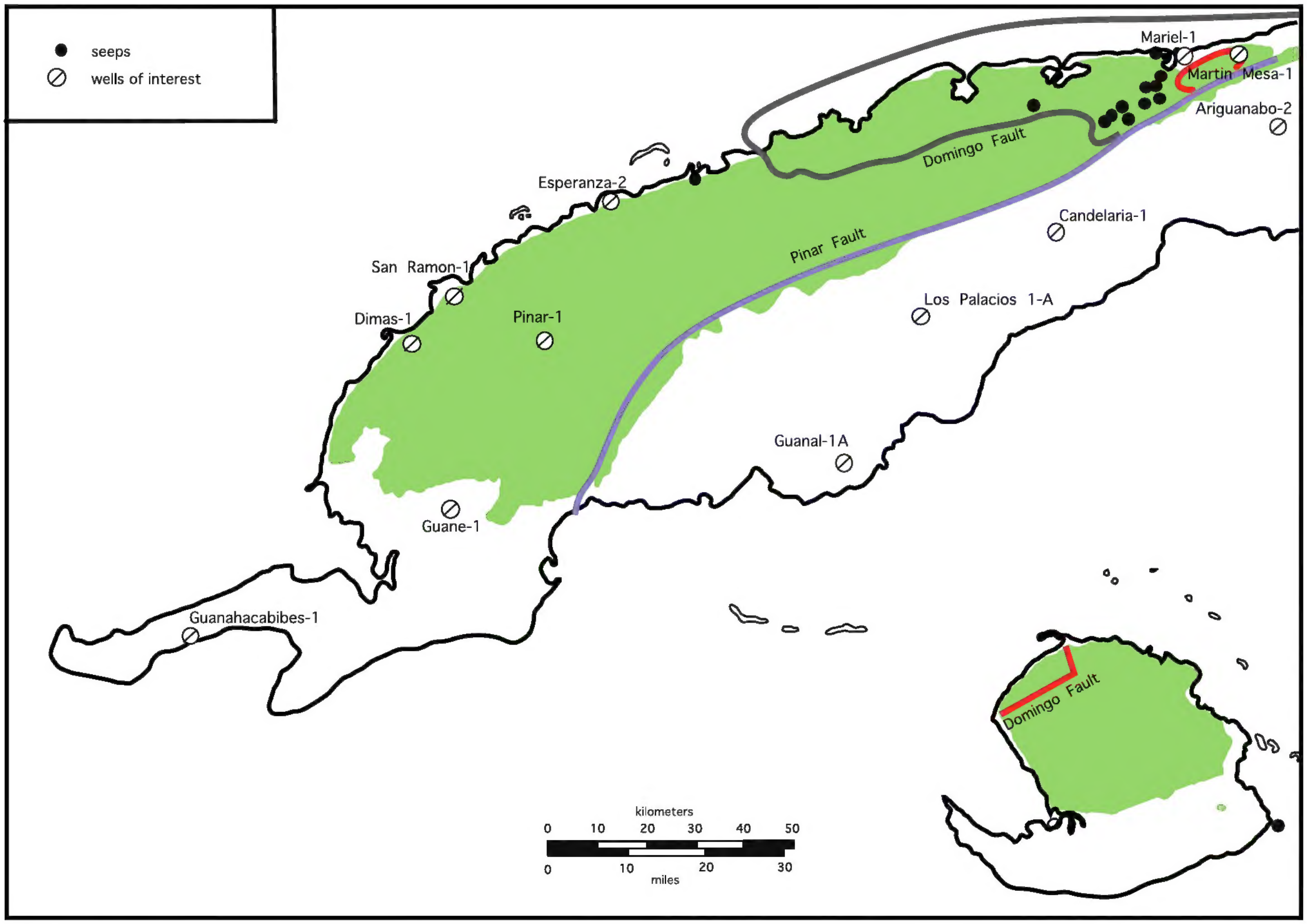

FIGURE 195. **Western Cuba: petroleum seeps, oil fields, and significant wells.**

and deposits are common, especially when the Eocene and Cabaiguan* sequence equivalent overlies this belt like in Martin Mesa between the Rosario Mountains and Guanajay. An oil seep exists along the coast near Puerto la Esperanza.

Subsurface Indications

Several wells have been drilled in the Rosario belt sediments, and most have had some shows and even some limited production. In general, the oil indications are similar to those found north of the Domingo* sequence and the Cifuentes* and Las Villas* belts of central and northern Cuba. The well EPEP Martin Mesa-1 has been reported as a discovery. This well on the north flank of the Martin Mesa window was drilled to 10,663 ft (3251 m). No published details exist as to the oil occurrence, but the well bottomed in the Neocomian, drilling through a thrust fault at ±5180 ft (±1580 m) that repeated the Aptian through Maastrichtian sequence. The section is an equivalent of the northern Rosario belt.

Sierra De Los Organos, Pizarras del Sur, and Cangre Belts

Surface Indications

No seeps are known from these belts; most of the outcrops consist of barren-looking San Cayetano Formation clastics, although some Jagua Formation and Viñales Group carbonates show bituminous material.

Subsurface Indications

The well EPEP Pinar-1, drilled 4 km (2.4 mi) south of the town of Pons in the central Organos belt, found oil saturation in fractures associated with faulting, in the lower autochthonous carbonate sequence. This section, extending from 12,136 ft (3700 m) to a total depth at 17,056 ft (5200 m), consists of Upper Jurassic bank-type limestones.

Domingo and Cabaiguan Sequences*

The Bahia Honda* belt ultrabasics are not well developed and do not have obvious seeps or production

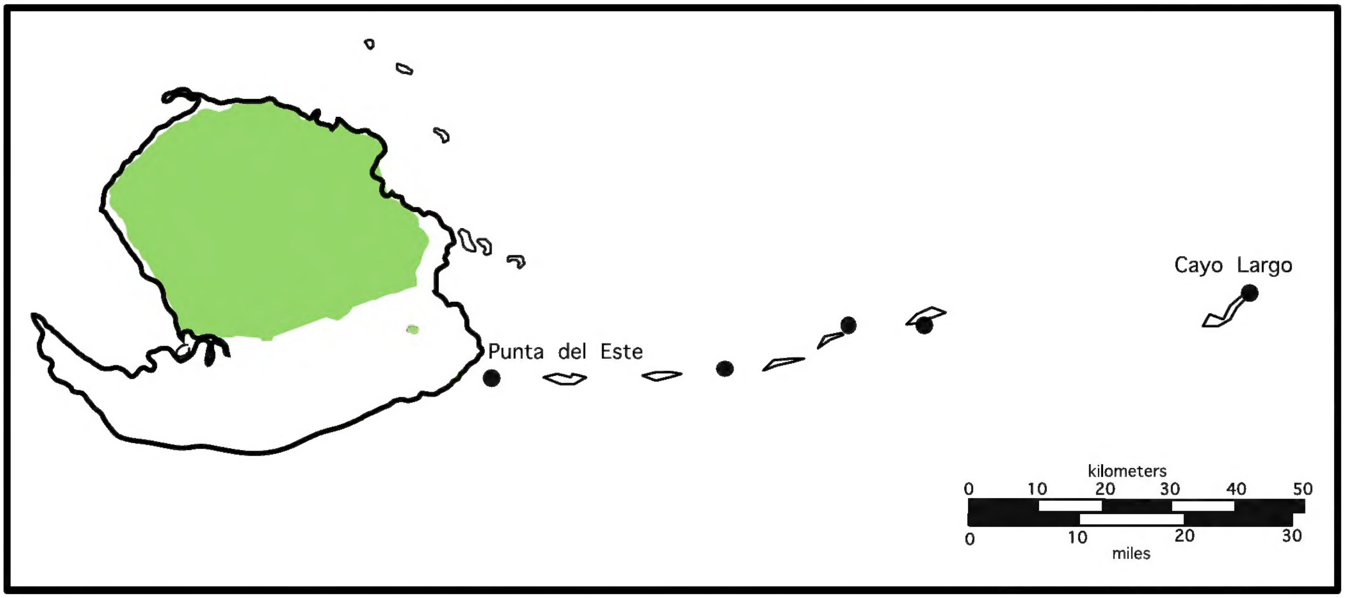

FIGURE 196. Western Cuba: Isla de la Juventud gas seeps.

as in central and northern Cuba. However, there are oil indications and asphalt deposits in the volcanics of the Bahia Honda* belt between Cacarajicara and Bahia Honda and between Mariel and Cayajabos, where they are in proximity to or possibly overlie the Rosario belt. At least nine asphalt mines have been exploited there in the past. EPEP's Mariel-1 and Mariel-2 were drilled to 10,171 and 10,312 ft (3101 and 3144 m), respectively, in Domingo* and Cabaiguan* sequence rocks (under the Miocene overlap) to a depth of ±7900 ft (±2400 m), where they encountered chaotic lower–middle Eocene conglomerates (La Vieja wildflysch = Rosas* Formation) to total depth.

No seeps have been reported in the San Diego de los Baños Basin. Several relatively deep tests (such as ARCO Baños-1 and Baños-2, EPEP Candelaria-1, Rosario Taco Taco-1, and Rosario Soroa-1) were drilled south of the Pinar fault in its Cabaiguan*-like volcanics and overlying thick Tertiary sediments. Although methane and oil shows have been reported, there has not been a discovery in the basin.

Western Cuba: Isla De La Juventud

A report of hard asphalt outcrop on the Isla de la Juventud proper, at Cerro Natividad, as well as on the keys north of the island was written (DeGolyer, 1918); this is difficult to believe and has not been subsequently confirmed. In addition, several gas seeps have been reported along the keys that extend eastward from the Isle of Pines from Punta del Este to Cayo Largo (Butticaz, 1952) (see Figure 196). Two of the gases were analyzed and show 71 and 74% nitrogen, 12 and 24% methane, 16 and 0% hydrogen sulfide, and 1 and 2% carbon dioxide, respectively. These gas seeps are apparently quite active and build small underwater sediment cones. The origin of these gases is somewhat puzzling; the methane, hydrogen sulfide, and carbon dioxide could be either of recent organic origin, associated with hydrocarbon gases or of volcanic origin. However, little is known about the origin of high percentages of nitrogen, assuming that the chemical analyses are reliable. In other areas, it has been suggested that the nitrogen is produced by the breakdown of ammonia resulting from the decomposition of organic matter.

Northern Cuba

As previously mentioned, the outcrops on this part of the island consist of a complex structural mixture of Domingo* and Cabaiguan* sequences. However, the Las Villas* and Cifuentes* belt lithologies have been recognized at depth in many of the wells (see Figure 197).

Surface Indications

As mentioned in the Introduction, the Spanish colonists in 1508 knew of the presence of tar in Habana Bay. The petroleum seeps at the baths of Guanabacoa, now an eastern suburb of Habana, were also well known in colonial days. Seeps are common along the north coast of the island and at the type locality of the Universidad Formation, in the grounds of Habana

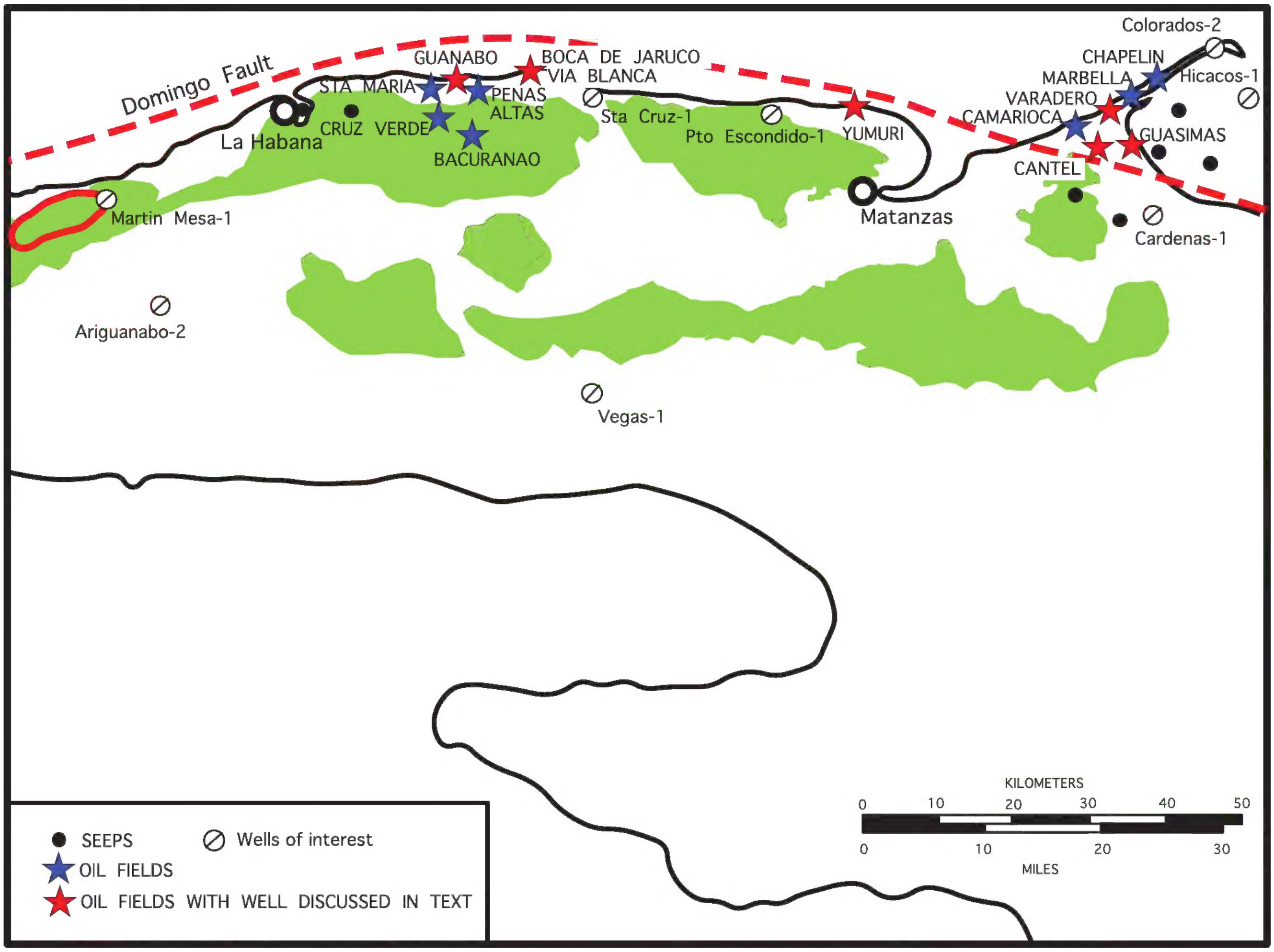

FIGURE 197. Northern Cuba: petroleum seeps, oil fields, and significant wells.

University; this unit is impregnated with heavy oil. In Cardenas Bay, tar is coming to the surface of Holocene sediments along what appear to be fractures and forming underwater accumulations. These were mined at several localities from 1875 to the early 1900s. It should be mentioned that these tar seeps were reported as replenishing themselves. Cardenas Bay lies mostly over the northwest projection of the Cifuentes* belt and its contact with the Domingo* sequence.

Subsurface Indications

Many water wells drilled in this general area have had oil and gas indications. This is also true of the many shallow holes drilled near seeps.

Gulf Hicacos-1 was drilled in northeastern Cardenas Bay in 1949. It penetrated the Las Villas* belt at 2290 ft (698 m) to total depth at 5045 ft (1538 m) below an Eocene to Holocene cover and was cut by at least one major fault at 4030 ft (1229 m) that brings lower–middle Eocene under the Upper Jurassic Caguaguas* Formation. The section immediately below the upper Eocene marls consists of fractured Cretaceous limestone, saturated with tar for 539 ft (164 m). The tar sometimes forms a high percentage of the rock, strongly suggesting an Eocene seep. The entire Jurassic–Lower Cretaceous section contains numerous heavy-oil indications.

Since 1960, there has been much drilling, with some of the wells deeper than 12,000 ft (3700 m). The detailed results are unknown, but led to the discoveries of Varadero and Boca de Jaruco fields.

Oil Fields

Several oil fields are located between La Habana and Cardenas Bay. They are named, from west to east, Bacuranao-Cruz Verde, Santa Maria del Mar, Guanabo-Brísas, Peñas Altas, Boca de Jaruco, and Via Blanca fields in Habana Province, and Yumurí, Camarioca, Cantel, Varadero, Guasimas, Marbella, and Chapelin fields in Matanzas Province. Many of these are old inactive

fields, but Boca de Jaruco and Varadero have been recently developed and are reported to contribute the great bulk of today's Cuban production. From the sparse literature, they appear to be similar in general character and regional structural position to those of Jarahueca and Motembo; they are located on or near the northern outcrops of the Domingo* and Cabaiguan* sequences, in proximity to and/or over the Cifuentes* and Las Villas* belt rocks.

Published information on these fields is somewhat vague and very limited, with no maps (well location, reservoirs, etc.) and no production statistics. The stratigraphic nomenclature does not follow the terminology of the other Cuban publications. The sections are invariably described as stacks of strongly folded para-autochthonous, allochthonous miogeosynclinal to allochthonous eugeosynclinal material separated by south-dipping, low-angle thrust faults. However, as described in Chapter 2 of this publication, it is possible to give a reliable limited translation of these terms to the nomenclature followed in this report.

Bacuranao-Cruz Verde

This is the oldest of the northern Cuba fields. Bacuranao was discovered in 1914. It produces 25–28° API oil from fractured serpentine (Domingo* sequence) from 200 to 800 ft (60 to 250 m). The gross pay is 300 ft (90 m). The deepest well was drilled to 7665 ft (2336 m) and encountered conglomerates and sandstones below the serpentine. The field began production in 1916 and was abandoned in the 1940s. Cruz Verde started producing in 1955, and Bacuranao went back on stream in the early 1960s. The maximum production was 146 BOPD in 1958 and was 74 BOPD in 1964.

Santa Maria Del Mar

The discovery well Ted Jone Jones Bess-1, drilled in 1955, is reported to have encountered 15–28° API oil at 2200 ft (670 m) in fractured serpentine (Domingo* sequence) and vugular dolomite. The serpentine is overlain by 1065 ft (325 m) of Maastrichtian volcanics and clastics possibly belonging to the Via Blanca and older formations (Cabaiguan* sequence). These, in turn, are overlain by 350 ft (105 m) of lower–middle Eocene and younger Tertiary. This field produced a maximum of 78 BOPD in 1957 and was producing 14 BOPD in 1964.

Guanabo-Brisas

The discovery well Ted Jone Jones Juanita-1, completed in 1956, encountered 8–11° API oil in tuffaceous sandstones and volcanic flow rocks at ±2200 ft (±670 m). The accumulation is reported to be in highly folded sediments under an unconformity. The maximum production was 98 BOPD in 1958, and in 1964, it was producing 3 BOPD. A pilot steam injection program was started in 1966, but there is no information about the results.

Boca de Jaruco-Via Blanca

This field was discovered in 1969 and is drilled largely offshore. The production consists of 17° API oil with high sulfur content. The structure is very complex and consists of a stack of two major thrust sheets. In the south of the field, downdip from the crest of the structure, the section has been described under Drilling, Cifuentes Belt, Chapter 2 of this publication.

An autochthonous section has not been penetrated, and oil is being produced from fractures in the sections under the two major thrusts. The top of production for each zone is −1500 ft (−450 m) and −2700 ft (−825 m), respectively. The reported initial recoverable reserves are given as 6 MMBO.

Varadero

It is the largest field discovered so far; it was discovered in 1972. The production consists of 17° API oil with high sulfur content. H_2S has been reported. The structure is complex and consists of a folded major thrust sheet with at least one imbrication. The section downdip from the crest of the structure has been described under Drilling, Cifuentes Belt, Chapter 2 of this publication.

The bulk of the production comes from the structure under the major thrust fault, which consists of a fractured anticline in the Las Villas* belt section. The top of the pay is at −2130 ft (−650 m), and the oil–water contact is at −3400 ft (−1050 m).

An autochthonous section has not been penetrated, and the reported initial recoverable reserves are given as 30 MMBO.

Not much published data exist on the Peñas Altas, Camarioca, Cantel, Chapelin, Guasimas, Marbella, and Yumuri fields. Some information indicates the following: (1) The section and accumulation in Peñas Altas are very similar to those of Boca de Jaruco; (2) Chapelin and Marbella have a section similar to that of Varadero and also produce from the Las Villas* belt rocks; and (3) Camarioca, Cantel, Guasimas, and Yumuri also consist of a stack of thrusts and produce from the Cifuentes* and/or Domingo*–Cabaiguan* sequence rocks. For a generalized cross section of the fields in the Varadero vicinity, see profile II′ across area 3 insert in Cuba, 1988.

Eastern Cuba

There are some confirmed oil indications in Oriente. According to DeGolyer (1918), the Farola asphalt seep, occurring in serpentine, was mined in the past. This occurrence cannot be located, but Cuba (1988) shows two seeps in serpentine south and near Puerto Padre. However, over the years, several wells (such as Transcub Embarcadero-1, Benedum Eugenia-23/1, Transcub Manzanillo-1, and Transcub Rio Tana-1) have been drilled in and on the flanks of the Cauto Basin without any encouragement.

SOURCE ROCKS

In Cuba, abundant sediments would be considered classical petroleum sources. However, there is no assurance that the oil presently found on or near the surface originated entirely from these sources. The maturation and migration history might not have been favorable for the formation of petroleum deposits at the proper time. It is unfortunate that at the time of the original Gulf studies, hydrocarbon analytical techniques and the present concepts of the origin, maturation, and migration of oil were either nonexistent or in their infancy. Today, much better quantitative studies could be done along the lines of source beds, maturation, correlation of potential sources with produced petroleum, and between different petroleum types. Although many of the fundamental problems of the origin of oil remain to be solved, the geological complexities of Cuba render the task of understanding the relationships between source and possible accumulation highly speculative. A problem in assembling this study is the absence of published data based on modern geochemical techniques.

It should be pointed out that the association of oil and gas seeps with ultrabasic rocks is not unique to Cuba. Almost every major Mesozoic to Tertiary ophiolitic area in the world has petroleum indications: Greece, Turkey (both known since antiquity), the Zagros Mountains in Iran, New Zealand, and the Franciscan complex in California are among the better known ones. In every case, the explanation given for the petroleum occurrence is that the ophiolite was thrusted over, or intruded into, petroleum-generating sediments. Although this is a likely explanation, one should keep an open mind to the possibility of a yet-unknown process. Szatmari (1989) proposes a Fisher-Tropsch oil-generation process (high-temperature hydrogenation of carbon monoxide from carbonates) during the obduction of serpentine over carbonates.

As seen in the preceding section, there appear to be two kinds of oil in Cuba. The oils associated with the basic igneous and the volcanics are medium to high gravity, low viscosity, paraffinic, and with low to no sulfur content. The oils associated with the carbonates are low gravity and high viscosity and have a high sulfur content; hydrogen sulfide is occasionally present.

Obvious Possible Sources

The following Upper Jurassic and Cretaceous units appear to be good candidates for petroleum source rocks:

Central Cuba

With some exceptions, central Cuba does not exhibit sediments with an apparent high (present-day) organic content in outcrop. The colors are generally tan to gray, and as already mentioned, tar and oil indications in outcrops here are not as spectacular as in Pinar del Rio. However, this could be the result of a deeper weathering of central Cuba, as well as less well-developed Jurassic exposures.

Las Villas Belt*

The exposed Jurassic Hoyo Colorado*, Jaguita*, and Caguaguas* formations consist of massive limestones, laminated limestones with oolitic intervals, and medium-grained dolomites. They indicate an alternation of shallow-water carbonate bank deposits with an oxidizing environment and deeper water pelagic deposits. They correlate with and are similar to the Pinar del Rio, San Vicente, and El Americano members of the Guasasa Formation.

The Berriasian to Barremian Capitolio* Formation is a gray, massive, biomicritic limestone, with thin wavy laminations and numerous secondary chert nodules. It consists entirely of nannoconids, calpionellids, and radiolaria skeletons with common aptychi and was deposited in deep waters. The gray color, the preservation of the nannoplankton, and the lack of bottom-dwelling organisms suggest anoxic conditions. This unit is similar and equivalent to the Sumidero Member of the Artemisa Formation.

The Aptian to Cenomanian is represented by the Penton*, Calabazar*, and Mata* formations that consist of alternations of thin-bedded, and at times laminated, limestones and primary radiolarian cherts. These units are essentially of pelagic origin. The only exceptions are thin layers of bioclastic turbidites

originating from the shallow carbonate banks. The Calabazar* Formation is characterized by black cherts and limestones that are dark gray when fresh and weather to chalky white, indicating abundant organic, bituminous matter. These units correlate in part with the Pons Formation.

Placetas and Cifuentes* Belt*

The Berriasian to Barremian is represented by the Ronda* Formation. This unit has similar textures and compositions, and it is therefore similar, in environment of deposition, to the Capitolio* Formation of the Las Villas* belt. The amount of argillaceous material and organic content increases toward the southernmost facies, as indicated by the change from brown to black color.

The Aptian to Cenomanian is represented by sediments that range from the above described Calabazar* and Mata* formations of the Las Villas* belt through the Carmita* Formation assemblage of limestones, cherts, thin-bedded shales, and fine-grained sandstones of the Placetas* belt to the Santa Teresa* Formation of the Cifuentes* belt, consisting entirely of thin, even-bedded, varicolored cherts (radiolarian) and shales. This entire group of formations is of pelagic origin and may have had source potential not too unlike the Monterrey of California. This, however, is difficult to assess at present.

Cabaiguan Sequence*

The only unit that appears to have source potential is the Gomez* Formation, of Cenomanian age, which, in the exposure of its best development on the north flank of the Seibabo syncline, consists of thin-bedded black and brown pelagic limestones interbedded with dark-gray shales. Although the thickness at this locality, 500 ft (150 m), is adequate to generate hydrocarbons, the regional distribution of this facies is not known.

Western Cuba

The rocks outcropping in this province display some very spectacular examples of what today is considered a classical source rock. They are found mostly in the Jagua Formation and the Viñales Group, particularly in the Rosario belt. Black bituminous pelagic limestones, black shales containing ammonite-bearing concretions that release oil when broken, as well as limestones that give a strong sulfurous and bituminous odor when freshly broken are present. The units that are considered good candidates for a petroleum source are as follows.

Sierra de los Organos Belt

The Jagua Vieja Member of the Jagua Formation, of upper Oxfordian age, consists of black laminated shales with ammonite-bearing limestone concretions; the concretions contain oil (commonly inside the ammonite chambers).

The Guasasa Formation, of Kimmeridgian to Cenomanian age, contains several black, micritic, pelagic, limestone members: the San Vicente and El Americano members.

The gray to black micritic limestones and cherts of the Pons Formation, of Valanginian to Turonian age, also have the classical characteristics of organic-rich sediments deposited under fairly deep and anoxic water conditions.

Northern and Southern Rosario Belts

The Francisco Formation is a correlative of and lithologically similar to the laminated and petroliferous Jagua Vieja Formation described above.

The Kimmeridgian to Valanginian Artemisa Formation, with its well-bedded micritic limestones and cherts, is equivalent to the lower Guasasa and is an even more favorable source. It appears to have been deposited under even deeper, pelagic, and anoxic conditions and is characterized by a strong petroliferous odor and the presence of asphalt.

The Buenavista Group and the Santa Teresa, Pinalilla, and Moreno formations, of Barremian to Maastrichtian age, containing abundant radiolarian cherts and, like the Las Villas Santa Teresa Formation, could have contributed hydrocarbons.

Northern Cuba

Here, the Las Villas* and Placetas* or Cifuentes* belt lithologies of central Cuba are present and are associated with the current production. These rocks, which act as reservoirs in several fields, are also believed to be the source of petroleum, particularly the Upper Jurassic ones.

Oriente

With the exception of isolated blocks of pelagic carbonates included in the ultrabasics of the Silla de Gibara area, no outcrops of any of the type of rocks described above exist.

Speculative Sources

In addition to the several potential petroleum source rocks mentioned above, some other possible, although speculative, sources should be discussed.

Central Cuba

Coastal Area: Jaguajay and Jatibonico* Belts*

The Jurassic and possibly older rocks underlying the shallow-water bank carbonates exposed or drilled in this area are essentially unknown. The deepest wells in a normal stratigraphic section or the most complete exposures of the Yaguajay* belt show less than 14,000 ft (4300 m) of section that is less than half the estimated depth to basement. The Gulf Blanquizal III-1, Texaco Mayajigua-1, and Shell Punta Alegre-1A wells bottomed in the Lower Cretaceous or questionable Upper Jurassic. Only in Shell Cayo Coco-2, the Yaguajay*, and the Jatibonico* belts was the Jurassic identified. Some of the ICRM deep wells drilled along the coast are reported to have penetrated the Jurassic, but no detailed information on them exists.

However, the outcrops at Punta Alegre and the Kewanee Tina-1, Kewanee Tina-2, and Kewanee Collazo-1 wells show a section dominated by Portlandian evaporites tectonically out of stratigraphic sequence. These, as well as the section in Gulf-Chevron Cay Sal-1 and Tenneco Doubloon Saxon-1, suggest a thick Lower Cretaceous and Jurassic carbonate and evaporite section. The question, of course, is whether the carbonates associated with the evaporites could have been good petroleum generators. No direct answer to this question exists; the Sunniland production of southern Florida, as well as the strong Sunniland oil shows in some wells off Key West, must have originated from limestones within this type of section.

Another problem is whether the San Cayetano Formation clastics are present under and/or partially equivalent to the Cayo Coco* Formation. The presence of these two formations in close proximity is supported by the fact that the San Adrian gypsum diapirs, in northern Matanzas, contain abundant exotics of sandstones and shales identical with those that make up the San Cayetano Formation in Pinar del Rio. The San Cayetano Formation has not been traditionally considered a favorable source, but this will be discussed under the section on Western Cuba in this chapter.

The carbonate muds and bioclastic platform sediments of the Lower Cretaceous upper Cayo Coco* and Guillermo* formations could conceivably have been sources of petroleum under the proper temperature conditions for the reasons given above, although they are not prime candidates; this is where kerogen studies of the available samples of some of the wells are needed.

The Aptian–Turonian is represented by the thin-bedded limestones, shales, marls, and black cherts with abundant pelagic organisms of the Guillermo*, Romano*, and Contrabando* formations. These pelagic units appear to be limited to the Cayo Coco–Punta Alegre area. They could either represent deeper water tongues separating shallow-water carbonate banks (Upper Cretaceous Old Bahamas Channel) or be limited by Upper Cretaceous structural conditions. It should be noted that there is a regional discontinuity between the Lower Cretaceous massive carbonates and the Upper Cretaceous pelagic marls in parts of the Bahamas and Florida. Their value as a source is unknown, but it is not considered to be very high.

Las Villas Belt*

The base of the section is not exposed. The dolomitic Hoyo Colorado* Formation, of Tithonian age, could be underlain by a Cayo Coco* facies and even by the San Cayetano Formation. This, as previously mentioned, is definitely suggested by the exotics in the San Adrian gypsum diapirs. If the evaporites and/or the shales formed a décollement surface at the base of the Las Villas* belt, it could be riding over the carbonate bank facies and its speculative source rocks.

A major unknown, from a source standpoint, are the once widespread and thick (over 3000 ft [900 m] exposed in the Jatibonico area) flysch deposits of lower–middle Eocene age of the Vega* and Rosas* formations. These terrigenous deposits, with limited present-day exposures, had a very active source of sediments from the south. They were deposited in deep waters and were rapidly buried under the advancing, thick, orogenic front. They served as a gliding surface for the Domingo* thrust and the Cifuentes*, Placetas*, and Las Villas* belt imbrications. Organic matter is not obvious in outcrops, where the Vega* Formation is invariably deeply weathered because of its content of feldspars and mafics. In cores, however, oil can be seen seeping out of freshly cut boulders. If these sediments were a source, it could explain the suggested terrestrial clastic origin of the oil sample from Gulf Sullivan-8. It could also explain the abundance of oil indications in the Domingo* sequence and along the fault separating it from the Las Villas* belt where the Vega* Formation is always found crushed along the fault plane. Most importantly, it would explain the difference between the oils of Domingo* and Cabaiguan* sequences and those associated with the carbonates.

The Vega* Formation is also the only known synorogenic sedimentary unit structurally below the Domingo* sequence, with a large-enough thickness and clay content and low-enough permeability to be able to maintain geostatic pressures for some appreciable period of time. This is considered essential to generate

the necessary hydrodynamic gradient for the migration of hydrocarbons. It is possible that the serpentines could have had a similar behavior. Geostatic pressure is certainly indicated by the asphalt dikes in the Domingo* sequence.

Domingo Sequence*

As previously mentioned, in the general Santa Clara area, there are outcrops of Maastrichtian, noncalcareous, shales of the Miguel* Formation that were deposited under pelagic conditions, which appear to structurally underlie the Domingo* sequence. Nothing is known about the original thickness and distribution of these deposits, which could have generated hydrocarbons under the right circumstances.

Escambray Massif

It should be mentioned that the low-grade metamorphics in the core of the mountains contain quartzites interbedded with gray graphitic mica schists: the Naranjo Group that ranges from the Lower Jurassic to the Oxfordian. These are overlain by dark-gray to black limestones with sulfurous odor: the Sauco and Mayari formations that range from the lower Tithonian to Lower Cretaceous. In the rim of the mountains, there are some higher grade metamorphics consisting of black marbles and schists with graphite of the Collantes Formation of equivalent age. These units, which are similar to and correlate with parts of the Pinar del Rio section, at some pre-Upper Cretaceous time, could have contributed hydrocarbons prior to metamorphism.

Western Cuba

The San Cayetano Formation has not been traditionally considered a source rock. This is caused by the abundance of coarser clastics, to some variable degree of metamorphism, to its usual white to reddish color in the outcrops, and to the absence of seeps or other oil indications. However, the formation is very thick (estimates of up to 15,000 ft [4600 m] have been made) and consists of a well-bedded alternation of sandstones, siltstones, and shales, commonly barren of organisms; it is of black to dark-gray color when fresh. Plant remains and carbonaceous material are present. It appears to be a typical deltaic sequence, and one could expect associated prodelta muds. This entire section certainly shows many petroleum source characteristics that would also be compatible with the suggested origin of the oil in Gulf Sullivan-8.

The San Cayetano Formation equivalents certainly covered a large area in addition to Pinar del Rio. They outcrop as exotics in the San Adrian diapirs and, exhibiting various degrees of metamorphism, in the Isla de la Juventud (Cañada Formation) and in the Escambray massif (Naranjo Formation) in Las Villas Province. It would be of interest to ascertain if some of the exotic metamorphic blocks found in the serpentine in the vicinity of the town of Santa Clara could be related to the San Cayetano.

In addition, near the top of the section and equivalent to part of the Jagua Formation are beds of black fossiliferous limestones, with a strong sulfurous odor when broken, which appear to have been deposited in an anoxic environment.

MATURATION

If one accepts all the units described in the previous section as potential sources, the best that can be done at present is to try to make reasonable assumptions regarding the maturation and possible migration of hydrocarbons.

Temperature

The first point to consider is that, in the Escambray massif, the age of the youngest metamorphosed sediments, the Loma Quivican Formation, is believed to be pre-Campanian Upper Cretaceous. If the internal thrusting of the massif is prior to the metamorphism and the apparent inverse metamorphism is caused by the overriding by the Domingo*–Cabaiguan* thrust plate, as was initially proposed by Millán and Somin (1981), the metamorphism must be Maastrichtian or later. If the thrusting within the massif is postmetamorphism and the apparent inverse metamorphism is caused by the stacking of several plates of increasing metamorphic grade, then the metamorphism must be related to the post-Cenomanian Upper Cretaceous volcanic arc. Regardless of whether one considers that the Domingo* and Cabaiguan* sequences rode northward over the Escambray massif or that the Domingo* and Cabaiguan* sequences were extruded by the closing of the back-arc between the North American continental margin and the Escambray massif, the metamorphism should have occurred when the Escambray rocks were much farther to the south or west of their present position. Thus, in either case, the entire succession from Lower Jurassic through the Cretaceous and from the southern coast of Cuba to the Bahamas should have had a normal continental margin thermal regime up until the early Eocene. It should be noted that neither the carbonate belts nor the Cabaiguan* and Domingo* sequences show any indication of thermal metamorphism. The same is true in Pinar del Rio. The

metamorphism in the Cangre belt is interpreted as a separate thrust sheet adjacent to the Pinar fault.

The information available on temperature comes from three sources:

1) Kewanee Collazo-1 and Gulf Hicacos-1. In bottom-hole temperature measurements, they show a very low geothermal gradient of 0.45°F/100 ft (0.82°C/100 m).
2) General Corporation Echevarria-1. A temperature log from the uncased well in the Cabaiguan* belt shows a somewhat higher, but still low, gradient of 0.83°F/100 ft (1.51°C/100 m).
3) Published heat-flow measurements from 35 boreholes by Cermak et al. (1984, 1991) (see Chapter 5, this publication). The given temperature gradients are as follows:

   Coastal area: Punta Alegre: 0.37°F/100 ft (0.68°C/100 m)
   Organos–Pinar del Rio: 0.75°F/100 ft (1.37°C/100 m)
   Domingo* or Cabaiguan*–north coast: 1.16°F/100 ft (2.11°C/100 m)
   Domingo* or Cabaiguan*–Cardenas Bay: 1.66°F/100 ft (3.03°C/100 m)
   Cabaiguan*–Jatibonico oil field: 2.14°F/100 ft (3.90°C/100 m)
   Cabaiguan*–Central Depression–western Camaguey: 1.34°F/100 ft (2.43°C/100 m)
   Cabaiguan*–central Camaguey: 0.83°F/100 ft (1.51°C/100 m)

Because the data from 1 and 2 are taken from logs and are uncorrected, they probably tend to underestimate the true gradient. The data from 3 are believed to be much more representative because the boreholes stabilized over a period of years before the measurements were made. However, the measurements taken in the continental margin show very low values, 0.45–0.75°F/100 ft, whereas those taken in the Domingo*–Cabaiguan* sequence are appreciably higher, 0.83–2.14°F/100 ft.

A Model

A greatly oversimplified picture of the structural evolution and distribution of lithologic units was considered.

The model depicts the following conditions:

1) That the San Cayetano and equivalent Cayo Coco* and Punta Alegre* formations, as well as older unknown facies, represent the filling of a subsiding rift, with sedimentation more or less keeping pace with subsidence.
2) That there was a continuous regional subsidence from Berriasian to the end of the Cretaceous with, to the north, the Yaguajay* and Coastal Province carbonate sedimentation keeping pace with the subsidence, whereas the belts to the south did not and received only pelagic sedimentation in waters on the order of some 13,000 ft (4000 m) deep.
3) That the thrusting started in early Tertiary, producing deep-water flysch deposits, the Vega* Formation, which were overridden in middle Eocene by the Domingo*–Cabaiguan* sequences thrust sheet, the whole process terminating before the upper Eocene.
4) That only relatively minor later activity occurred because no upper Eocene and later detrital deposits are well developed in Cuba (they could be present offshore). Consequently, the pre–upper Eocene and later erosion in central Cuba and Pinar del Rio were ignored.

Using surface temperatures of 25°C at sea level and 5°C in deep water, paleodepth and paleotemperature diagrams for two hypothetical locations were prepared: at a north location on the carbonate bank and a south location inside the thrust belt. Two oil-generation modeling techniques, the Lopatin and Arrhenius methods of calculating the time-temperature indices (TTI), were used for each location (Waples, 1980; Wood, 1988). The Arrhenius technique gives somewhat more optimistic results than the Lopatin.

The following results were obtained:

1) If the entire continental margin had a geothermal gradient of 1°F/100 ft (1.824°C/100 m), then, at the northern location, only the Jurassic and the lowermost part of the Cretaceous would have been subjected to a high-enough temperature during a long-enough period of time to have generated petroleum; however, neither technique indicates that Cretaceous rocks reached the peak of oil generation. Moreover, the temperature at the southern location would have been affected by increased water depth and by the thrusting. Only the Lower Jurassic (if it exists) would have been under the right conditions until the lower Eocene and the entire Jurassic, Lower Cretaceous, and possibly the Upper Cretaceous, and the lower part of the Eocene flysch might have generated oil afterward. In other words, this suggests that oil

generation from the obvious sources might have been the direct result of the overthrusting.

2) If the southern Bahamas–northeastern Cuba had a gradient of 0.5°F/100 ft (0.912°C/100 m), only the Lower Jurassic (if it exists) would have been under favorable conditions at the north location.

In conclusion, these calculations, obviously very approximate, suggest that, unless (1) there is an unknown source older than anything observed and (2) the geothermal gradient was in the vicinity of 1°F/100 ft (1.824°C/100 m), the Cuban carbonate platform province had little chance to generate much oil. Tenneco's Doubloon Saxon-1, with a total depth at 21,740 ft (6628 m), should furnish critical information when the data are released.

However, they also suggest that the oil observed in Cuba at present is the result of the orogenic process that provided the necessary overburden for the maturation of the organic matter in the obvious possible and also speculative source sediments. It should also be noted that because of the low geothermal gradient (1°F/100 ft; 1.824°C/100 m) the maximum depth of wet-gas preservation could be on the order of 23,000–26,000 ft (7000–8000 m).

MIGRATION AND ACCUMULATION

This is unquestionably the aspect of Cuban petroleum geology that is most critical and most difficult to resolve. In most geosynclinal petroliferous basins, the deeper part of the basin, with a high percentage of argillaceous material and a greater thickness of sediments, is considered the source of petroleum as well as the source of high fluid pressures that drives the hydrocarbons toward the stable margins of the basin where they accumulate in traps (hydrodynamic sinks).

Therefore, the possible sources of fluid, the potential aquifers or reservoirs, and finally, the seals will be discussed.

Source of Fluids

All sediments are a potential source of fluids; quartz sands and most carbonates have an original water content on the order of 45%, and the clays and pelagic oozes on the order of 70%, which can be reduced to a few percent by normal compaction. However, only the clays will be able to generate overpressures because of their low permeability and swelling pressure; all the other sediments will generate overpressure only if they are enclosed within low-permeability sediments such as clays or evaporites (this is a complex and dynamic process). In Cuba, thick and extensive argillaceous sediments are known only in the Jurassic San Cayetano Formation (and related metamorphics), the Cretaceous Cabaiguan* sequence volcanics, and the lower–middle Eocene Vega* Formation flysch and equivalents. The Cabaiguan* sequence volcanics contain abundant argillaceous material, but are unlikely to have been involved in the petroleum-generation process; only the San Cayetano and the Vega* formations could have been an important factor.

The San Cayetano Formation is the only unit suggesting a deltaic sequence certainly capable of generating overpressures. One can safely assume that, at least until the end of the Cretaceous, it had a fairly normal compaction gradient, similar to that found in many present-day deltas. Whether the San Cayetano Formation and equivalents could have developed and maintained overpressures for any length of time would have entirely depended on the shale percentage distribution, and no data on this subject are available. Furthermore, if overpressures existed, the direction of fluid flow during the Jurassic and Cretaceous would have depended on the paleogeographic reconstruction of the sand and shale facies.

Central and Northern Cuba

In the Escambray massif, where the metamorphosed equivalents of the San Cayetano are present, if one assumes that the direction of internal thrusting was from south to north, then the La Llamagua sands were to the north, and the Herradura shales were to the south prior to the thrusting. This indicates that the direction of compaction fluid flow during the Jurassic and Lower Cretaceous was from south to north.

During the orogeny in uppermost Cretaceous to middle Eocene, the direction of fluid flow must have been controlled by the advancing thrusts and, therefore, must have been from south to north over much of central Cuba.

Farther to the north, in the Cayo Coco–Punta Alegre area of the coastal province, the abundant evaporites must have channeled the migration of fluids southward toward the edge of the banks. The geometry of the possible transition from the Punta Alegre* (and/or lower Cayo Coco) Formation to the San Adrian (and/or San Cayetano) Formation, and its effect on fluid-flow patterns, is totally unknown.

However, no evaporites are present in the Yaguajay* and Jatibonico* belts nor in the Gulf Blanquizal-1. Collapse breccias in the dolomite are common in the wells and outcrops, indicating the solution of Lower Cretaceous and possibly older evaporites. However,

these two belts were near the bank edge, and few evaporites might have extended this far from the center of the basin. This would suggest that along the bank edge, there might have been a zone of cross-formational fluid flow of unknown age, but possibly as old or older than the early Tertiary. This zone might have prevented the hydrocarbons, generated during and/or prior to the orogeny, from reaching the carbonate platform province and, therefore, the Bahamas foreland.

The noncalcareous shales of the Maastrichtian Miguel* Formation could certainly have been a source of fluid, but unfortunately, they are known only in a few isolated outcrops.

The lower–middle Eocene Vega* Formation must have been a source of fluids with near-geostatic pressures acting, therefore, as an effective hydrodynamic seal for fluid flow from older strata. This is caused not only by its clay content and high shale percentage, but by its rapid deposition and burial under the advancing Domingo*–Cabaiguan* sequence thrust sheets. As mentioned previously, the presence of asphalt dikes or veins is a definite indication that geostatic pressures existed at one time at the base of the Domingo* sequence and in the underlying sedimentary belts. It is unfortunate that, because of the structural complications, the outcrops of the Vega* Formation are so poor that it is impossible to map the lithologies of this unit on a regional scale.

In northern Cuba, the carbonate bank facies has not been recognized and probably did not extend west of the Cardenas Bay, so the only movement of fluids there must have been directed northward toward the Gulf of Mexico.

Western Cuba

In Pinar del Rio, the San Cayetano facies distribution strongly suggests that during the Jurassic, and possibly later, a south to southwestward direction of compaction fluid flow existed.

The direction of fluid movement is more difficult to estimate during the orogeny because both northward and southward thrusting have been recognized. Although chaotic, flysch and wildflysch, orogenic detritus is widespread, no thick shales such as the Vega* Formation have been recognized in Pinar del Rio.

AQUIFERS AND RESERVOIRS

Clastics

Generally, in Cuba, good reservoirs of this type are very few.

Central and Northern Cuba

Here, the Jobosi* and Constancia* formations could be considered potential reservoirs if well developed. They seem to cover a large area. However, where they have been observed, they are thin and have a dense calcareous matrix, although they have been reported as reservoirs in some north Cuba fields. It is not known if production is from intergranular or fracture porosity and permeability. Several volcanic-derived sandstones in the Cabaiguan* belt sequence exist, but they are quartz poor with a high percentage of feldspars and clays that reduce the permeability and effective porosity. The lower Eocene clastics of the Upper Vega* and Rosas* formations are believed not to have reservoir potential for the same reasons. Nothing is known of the possibilities of a San Cayetano Formation equivalent in this area; if present, its porosity might be greatly reduced by the additional overburden of the thrust sheets that could be on the order of more than 13,000 ft (4000 m).

Western Cuba

In Pinar del Rio, the San Cayetano Formation consists of a thick section of quartz sandstone interbedded with shales. The sandstone percentage can be very high, but it is impossible, because of structural complications, to determine the possible location of favorable sand/shale ratios. Although the sandstones in outcrops appear porous, they are invariably hard and well lithified when fresh. An additional problem is the variable degree of metamorphism. La Esperanza Formation also contains abundant sandstones, but very little is publicly known about it. The Tertiary Diego Formation outcropping south of the Pinar fault has numerous porous sands interbedded with shales that, under the right circumstances, could be good reservoirs.

Carbonates

These form the reservoirs in the largest fields (Varadero and Boca de Jaruco) and are the most likely potential reservoirs.

Central and Northern Cuba

In the Cayo Coco–Punta Alegre area and the Yaguajay* and Jatibonico* belts, the secondary dolomites found throughout the Lower Cretaceous and Upper Jurassic section are capable of being good reservoirs with adequate intercrystalline porosity and permeability. Platform limestones, if fractured near fault zones or other structures, are also possible reservoir beds. Vugular porosity and solution cavities are

occasionally found but are difficult to predict. Reefs are a definite possibility, but so far, they have not been observed. In the Las Villas* and Placetas* belts, the medium-grained dolomites of the Tithonian Hoyo Colorado* Formation appear to have enough porosity and permeability to be reservoirs. In addition, the associated massive shallow-water limestones, as well as those of the overlying Jaguita* Formation, could form good reservoirs if fractured. The same is true of the Lower Cretaceous pelagic limestones of the Capitolio* and Ronda* formations.

Western Cuba

In the Mogotes and Rosario belts, the massive limestones and dolomites of the Guasasa and Artemisa formations could be good reservoirs if fractured. Similar potential reservoirs are the several orogenic carbonate conglomerates found in every tectonic belt and the Cretaceous massive miliolid limestones of the Guajaibon Formation (Viñas* Group).

Other Rocks

Several other types of rocks form present-day reservoirs, such as fractured serpentine, gabbros, volcanics, and conglomerates. Whether these can produce sizable reservoirs with commercial flow rates is not known but unlikely.

POTENTIAL SEALS

As previously mentioned, a characteristic of the sediments exposed in Cuba is the lack of well-developed shales or other potential seals. Evaporites are found in the subsurface and outcrop only as diapirs; whether they can form continuous seals remains to be seen.

In all areas, it should be emphasized that the thrust faults themselves, with their Vega* (or similar) Formation material smeared along the fault plane, might form the best seals available. All surface and drilling evidence points to it. This type of seal apparently traps much of the present production. In view of the complexity of the fault geometry, whether it can be adequate for major accumulations remains to be seen.

Evaporites

North and Central Cuba

The evaporites of the coastal province are capable of being effective seals when present. They occur in the Cayo Coco–Punta Alegre area and could be extensive elsewhere in the northeastern coastal region. They are present in the Bahamas' Gulf-Chevron Cay Sal-1 and Tenneco Doubloon Saxon-1 wells. The dense limestones of this province are probably too fractured to be a barrier to fluid motion. Farther south, in the Yaguajay* to Cifuentes* belts, the known Jurassic and Cretaceous section is devoid of evaporites; however, there is the possibility that the autochthonous section with evaporites extends farther south and west under these belts as suggested by the presence of the San Adrian diapirs. Jurassic evaporites could be the décollement surface under the Yaguajay* and Las Villas* belt. If this was the case, autochthonous reservoirs could be sealed by the evaporites under the allochthonous belts.

Western Cuba

No evaporite beds have been definitely reported from Pinar del Rio. None of the logs of the Pinar del Rio wells, published in the 1985 geologic map (Cuba, 1985a), show evaporites. However, dolomite and anhydrite are reported by Kuznetsov et al. (1985) in the Puerto Esperanza wells, but not shown in the well logs. In the EPEP Pinar-1 well, Lopez-Rivera et al. (1987) report anhydrite, in nodules and fracture fillings, within the shallow-water Jurassic carbonates. The amount of anhydrite increases toward the total depth of the well at 17,058 ft (5200 m).

Argillaceous Sediments

Central and Northern Cuba

Except for the highly deformed Santa Teresa* Formation, the carbonate belts are essentially devoid of argillaceous material. The only known possibilities of argillaceous seals would be the Upper Cretaceous noncalcareous shales of the Miguel* Formation and the shales of the lower–middle Eocene Vega* Formation. Both units probably underlie the Domingo* thrust and are caught in the fault planes of the many imbrications.

In the northern Cuban oil fields, the seals over the existing production consist of Tertiary shales and graywackes, ultrabasics, and volcanics (olistostromes) caught along folded, faulted, and imbricated low-angle faults. This indicates that the faults behave as seals. However, it is the author's opinion that the complexity of the geometry of the observed faults has prevented the discovery of major accumulations. Perhaps there are some less complicated faults at depth or in unexplored areas.

As mentioned before, the fact that most of the active seeps are located in the ultrabasics of the Domingo* sequence suggests that these rocks, because of the fracturing, act more like a low-permeability reservoir

than a cap. However, the volcanics of the Cabaiguan* sequence do seem to act as a definite seal but they outcrop mostly in the trough of a large, faulted, sharp syncline.

Western Cuba

Here, the exposed Jurassic and Cretaceous nonvolcanic section shows a higher argillaceous content than that of central and northern Cuba. The San Cayetano, Jagua, and parts of the Artemisa, Polier, and Lucas formations have variable amounts of shale interbeds. In addition, some uppermost Cretaceous and Paleocene units like the Ancón, Buenavista, and Sierra Azul formations have well-developed shale beds. Unfortunately, their reported stratigraphic position is not too clear, and their relationship with older rocks, as suggested by the presence of volcanic outcrops within their described sections, could be of a structural nature. In the Los Organos belt, a detrital section of lower to middle Eocene age, the Pica Pica Formation, contains shales. This unit is fairly thin but suggests the Vega* Formation of central Cuba and could similarly be much more extensive and involved in the thrusting, making the thrusts themselves effective seals. The volcanics of the San Diego de los Baños belt, south of the Pinar fault, could provide some seals, but so far, despite all the drilling, no shows have been reported. In the same area, the Tertiary Diego Formation contains numerous shale beds.